



GHGT-9

# Quantitative risk evaluation related to long term CO<sub>2</sub> gas leakage along wells

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## Abstract

Carbon and Capture Storage is still bringing intensive worldwide R&D activities and significant growth of in situ CCS experiments. New technologies that enable and support the safety demonstration at each step of the CCS process are developed and already applied. Considering that old depleted hydrocarbon reservoirs or saline aquifers represent huge capacities for CO<sub>2</sub> storage, long term safety of confinement can be questioned by the well, stated to be one of the main intruders in the confinement system. Wells represent a potential vector for CO<sub>2</sub> to flow up from its storage formation to the surface or shallow aquifers. As a matter of facts, a specific attention has to be given to long term well integrity performance.

In the framework of its Performance and Risk (P&R<sup>TM</sup>) methodology, Oxand has developed a simulation platform called SIMEO<sup>TM</sup>-STOR that enables to quantify possible CO<sub>2</sub> leakages through a well, as a first step to well integrity performance and risk assessment. It combines a 2-phase flow model based on Darcy's law and degradation kinetics such as cement leaching/carbonation and casing corrosion to account for degradation phenomena associated with well components during the injection (i.e. short term) and storage period (i.e. long term). This solution constitutes an efficient technology to evaluate the CO<sub>2</sub> leakage towards targets (connected aquifers and/or surface) through wells. Because it enables to assess the global impact of a leakage with respect to the whole stakes involved in a CCS project, this tool provides operational elements as decision making support for project managers who have to deal with the possible occurrence of a failure event (i.e. well integrity performance).

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Keywords: well integrity, well degradation, Performance and Risks, risk analysis, SIMEO<sup>TM</sup>-STOR, CO<sub>2</sub> leakage modeling

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## 1. Introduction

Nowadays, people concern about the greenhouse gas emissions is growing. Both authorities and industrials are thinking about means to reduce their emissions in order to respect the convention signed in Kyoto. The CCS technology constitutes the most suitable technology to reduce greenhouse gases emissions to the rates expected in

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the coming years. Even though Carbon and Capture Storage is still bringing intensive worldwide R&D activities, a significant acceleration of in situ CCS experiments is observed to reach an industrial level. Pilots already exist worldwide: StatoilHydro is operating the Sleipner site (Norway) [2] by injecting CO<sub>2</sub> in Utsira formation (saline aquifer) since 1996, a consortium between BP, StatoilHydro and Sonatrach is injecting CO<sub>2</sub> on the industrial site of In Salah in Algeria [3], Encana is injecting CO<sub>2</sub> in Weyburn field [4] (Saskatchewan, Canada) to produce oil by EOR. These pilots are the most well-known existing ones, but a lot of feasibility studies or ongoing projects have reached enough technical maturity to start a pilot phase.

However, a large scale deployment can be questioned for some of them. Among various issues, public fear with respect to CO<sub>2</sub> geo-sequestration still constitutes a major challenge. Because of the uncertainty associated with the possibility for CO<sub>2</sub> to leak along the wellbore and its related impacts, it is of a paramount importance to be able to demonstrate that the wellbore constitutes a safe seal over the long term. A risk-based approach which integrates simulation tools for leakage quantification is necessary for long term safety demonstration.

This paper presents a quantitative risk-based methodology to evaluate the Performance and Risks (P&R<sup>TM</sup>) associated with well integrity [5–9] and proposes a description of the models used for CO<sub>2</sub> leakage quantification integrated in a simulation tool Simeo<sup>TM</sup>-Stor. An application case is then proposed to identify the key parameters to consider and the importance of the initial and limit conditions from a well integrity perspective.

## 2. Context and problematics

Risk is not just a concept but also a metric which can be quantified. Risk can be defined as the combination of the likelihood of a failure event (i.e. Probability P) and the magnitude of its impact (i.e. Severity S) (1).

$$\text{Risk} = P \times S \quad (1)$$

In the P&R<sup>TM</sup> methodology, a risk is estimated as follows:

- The failure event is represented by specific well integrity conditions (i.e. conditions that could lead to a leakage) to which a probability of occurrence is proposed.
- The magnitude of impact of a leakage is assessed with respect to all the stakes involved in a project (public acceptance, financial, reputation, know-how, health and safety, preservation of potable aquifers...).

The most important is the accurate identification of the different events that can appear in the present and in the future. Risk assessment includes the following steps:

- Risk identification: identification of all possible well integrity conditions which could lead to a CO<sub>2</sub> leakage
- Risk estimation: calculation of the probability of occurrence of the well integrity conditions and evaluation of their related impacts vs. a set of stakes
- Risk evaluation: acceptable and non acceptable risks are defined
- Risk treatment: well integrity solutions (characterization/inspection, design, monitoring) for non acceptable risks mitigations are proposed.

The Performance and Risks (P&R<sup>TM</sup>) methodology has been developed in accordance with this process. It includes modeling aspects in order to extrapolate existing knowledge along time by taking into account the well integrity degradations.

## 3. Performance and Risks (P&R<sup>TM</sup>) methodology – main steps

The P&R<sup>TM</sup> methodology (Figure 1) gathers different steps to go through for risk quantification and for recommending risk mitigation actions to ensure the well integrity performance.

After data collection, a static model of the well is performed. This model takes into account information about the well itself (description of geometrical and integrity parameters) and the near wellbore environment (geology). A functional approach of the well (the “system”) enables then to identify the functions of each well component and the processes that can impact the system integrity.

Then, a dynamic model is built by combining degradations kinetics to the static model. Such kinetics come from the interactions between the different fluids (formations fluids, CO<sub>2</sub>) and the well components (cement, casing steel). Initial and limit conditions of the system (hydrostatic and reservoir pressure, temperature...) are also set up in the dynamic model.



Figure 1: Performance and risks (P&R™) methodology workflow

As mentioned before, risk involves the notion of uncertainty on well integrity conditions which can be translated into probability:

- Initial cement permeability: uncertainty comes from the interpretation of CBL, VDL or TT data;
- Degradation kinetics: uncertainty comes from the knowledge gaps between experiments and in situ conditions;
- Incomplete data related to some well components (ex. surface casings are rarely logged, which leads to unknown casing conditions vs. corrosion and cement sheaths quality).

Uncertainties are interpreted as ranges of values. For a given parameter, the more uncertainties, the larger the distribution of values is. Dealing with both static and dynamic models, a “scenario” approach can be introduced to account for such ranges. Practically, a scenario represents possible well integrity conditions which parameters take a given value within the defined ranges. Then, all possible scenarios are simulated in order to quantify a CO<sub>2</sub> leakage over a given time period and corresponding CO<sub>2</sub> leakage pathways along the wellbore are identified.

Each leakage amount is then translated into a severity level by assessing the negative impacts vs. a set of specific stakes dedicated to the CO<sub>2</sub> storage project by means of a consequence grid. By crossing both severity and probability of each scenario, risk level is generated. Once all risk levels are quantified, they populate a risk matrix.

The set up of a Risk Acceptance Limit (RAL) in accordance with the stakeholders bring forward the non acceptable risk levels. Associated with the functional analysis, the analysis of the non acceptable scenarios allows identifying what are the contributors to the risk (i.e. the risk sources). Recommendations are finally provided to treat these contributors and thus to mitigate the risks considered as unacceptable for the project. Depending on the type of contributors, recommendations can be formulated. The typical mitigations actions can be classified in 4 main types:

- Characterization/Inspection, to clarify some uncertainties for the system,
- Design solutions, in order to decrease the occurrence of a well integrity failure which would generate a leakage,
- Operational solutions, to avoid unwanted consequences,
- Monitoring solutions, to detect and anticipate the occurrence of a leakage and to manage unwanted consequences.

#### 4. CO<sub>2</sub> leakage quantification

The CO<sub>2</sub> leakage quantification constitutes one of the main steps within P&R™ analysis. The outcome is a CO<sub>2</sub> leakage amount from the reservoir along the well and provides the possible leakage pathways and the targets impacted (surface, connected aquifer, other geological formations) to the operator. The CO<sub>2</sub> leakage quantificator implemented in SIMEO™-STOR combines porous media flow modeling and degradation models.

#### 4.1. Well zoning, Initial and limit conditions

Since the well degradations are function of the well interactors (geology, aggressive fluids, CO<sub>2</sub>...), the well modeling extends from the well axis to the near wellbore. In order to keep the model simple and practical, a 2D axisymmetric description of the well is used. Each geological layer has constant characteristics or properties. To be solved, the model is segmented by a process accounting for well components, geological formation layers and also cement sheaths heterogeneity in terms of quality. Segmentation is based on collected data (if only data at drilling date are available, data are processed to consider impact of production period on components' mechanical parameters). In addition, initial and boundary conditions need to be specified (initial water pressure profile along the wellbore, downhole storage pressure, flow conditions between cement sheaths and geological formations...).

#### 4.2. Porous media flow model

The model used is based on a darcian 2 phases flow model (i.e. wetting phase (w) and non wetting phase (nw)) where both phases are considered immiscible. Initially the cement is considered saturated with water, the wetting phase. To model the CO<sub>2</sub> flow in porous media and follow the water saturation evolution along time and space, a combination of the Darcy's law (2) and a mass balance (3) has been performed.

$$\vec{u}_w = \frac{-KK_{rw}(S_{nw})}{\mu_w}(-\nabla p + \rho_w \vec{g}) \quad (2)$$

$$\frac{\partial \rho_w (1 - S_{nw})}{\partial t} + \nabla(\rho_w \vec{u}_w) = 0 \quad (3)$$

$U_i$  represents the velocity,  $K_i$  the permeability,  $K_{r,i,j}$  the relative permeability,  $\rho_i$  the density,  $\mu_i$  the viscosity,  $\Phi$  the porosity,  $S_i$  the phase saturation,  $P$  the pressure and  $g$  the gravity. The relative permeability ( $K_{r,i,j}$ ) values are assessed from the Mualem (4, 5) and Van Genuchten (6) models in function of phases saturations ( $S_i$ ), capillary pressure ( $P_c$ ) and parameters ( $M, N$ ).

$$K_{r,nw}(\Theta) = \sqrt{1 - \Theta} \left(1 - \Theta^{1/M}\right)^M \quad \text{and} \quad K_{r,w}(\Theta) = \sqrt{\Theta} \left(1 - \left[1 - \Theta^{1/M}\right]^M\right)^2 \quad (4)$$

$$\text{with} \quad \Theta = \frac{S_w - S_{rw}}{1 - S_{rw}} \quad (5)$$

$$\left(1 + \left(\frac{p_c}{P_c}\right)^N\right)^{-\frac{1}{N}} = \frac{1}{\Theta} \quad \text{with} \quad P_c = P_{nw} - P_w \quad (6)$$

An Integral-finite difference method has been adopted. The system formed by the equations (1 -6) is solved by means of a Newton-Raphson method.

#### 4.3. Degradation models

Well components ageing models enable to estimate the evolution of components properties over time due to wellbore environment. Two mainly models are considered to describe the degradation mechanisms associated with the carbon steel tubulars and the cement-based materials. Model parameters such as corrosion rates and cement leaching/carbonation kinetics can be calibrated through experimental tests including accelerated testings and time-lapse well integrity monitoring measurements.

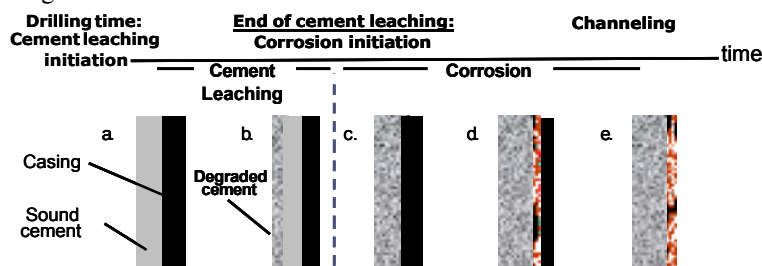


Figure 2: Degradation mechanisms implemented in SIMEO™ STOR

#### 4.3.1. Cement leaching

This article is not aimed at describing interactions between cement-based materials and formation fluids or  $\text{CO}_2$ . Such processes have already been studied [10–15]. Cement based materials are reactive porous media in which solid phases are in thermodynamic equilibrium with the surrounding pore solution chemistry. When in contact with acidic aqueous solutions, acid attack of cement-based materials takes place. The hydrates leaching process is essentially caused by the difference of composition and chemical activity between water in contact with cement and the pore solution inside cement. This difference of composition causes ions motion out of the cement, and subsequent dissolution of cement minerals (mainly hydrates: Portlandite, CSH). Cement leaching increases porosity and permeability and decreases compressive strength. The corresponding degradation front is diffusion dependent, progressing with square root of time. Degradation kinetic mainly depends on the fluid properties and the chemical composition of cement. It was assessed that the alteration front would progress upward at a rate of up to a few tenths of millimeters per year.

#### 4.3.2. Casing corrosion

Casing corrosion is a main ageing process to consider studying the long term well integrity performance. The physico-chemical phenomena are well described in literature [16–22]. Figure 2 shows that corrosion is envisaged once the cement leaching phenomenon is ended. The corrosion model for standard casings gives a linear relation between casing thickness and time. The factors determining the rate of corrosion are the temperature and  $\text{CO}_2$  partial pressure. Casing corrosion can occur through two different mechanisms: (i) generalized corrosion that occurs mostly at the casing surface, (ii) pitting corrosion, which takes place in presence of chlorides.  $\text{CO}_2$  corrosion is more significant in the presence of  $\text{CO}_2$  dissolved in water but becomes insignificant in dry supercritical flows.

### 5. Synthetic case application

The studied case presented in the following paragraph considers a typical abandoned well likely to be part of a  $\text{CO}_2$  storage project.

#### 5.1. Static model

The abandoned well described here is composed of 6 casings and their associated cement sheaths (Figure 3). The well has been plugged with four cement plugs. The geology is composed of classical formations likely to be found: a reservoir, a caprock, overburden and a connected aquifer.

According to the methodology described in Figure 1, the well and its near geologic environment are described in Simeo<sup>TM</sup>-Stor by their geometric and mechanical characteristics. The initial and limit conditions are also given for information (Figure 3). The highest uncertainty lies in the cement quality. For this study only the cement quality (for cement sheaths and plugs) has been considered as probabilistic.

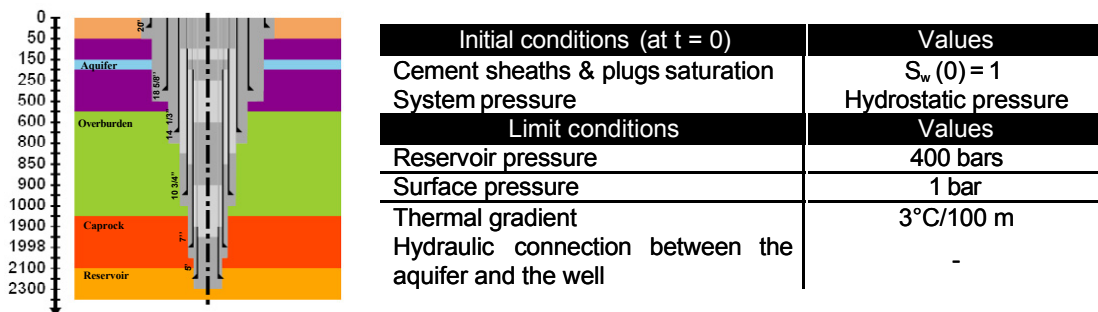


Figure 3: Static representation (SIMEO<sup>TM</sup>-STOR) of the abandoned well (not at scale)

Cement zones are defined by cementation data interpretation (CBL, VDL, TT...) Here, 5 cement zones have been highlighted and described by a probability law. For each cement zone, cement quality variations are modeled only by means of the vertical permeability value  $K_v$  (usually the most influencing parameter for  $\text{CO}_2$  flow up and

presenting the largest uncertainties ). The cement permeability values are ranged between  $10^{-3}$  mD for a very good cement, to 1 000 mD for a bad cement. In this study the other model parameters have been considered as deterministic. As a conclusion, only  $K_v$  values for the different cement zones will be randomized leading to 243 scenarios for possible well integrity conditions.

## 5.2. Results

### 5.2.1. $CO_2$ leakage amount

Figure 4 describes a possible leakage amount out of the  $CO_2$  reservoir along the well ( $CO_2$  enters the well) for one selected scenario. The  $CO_2$  leakage amount could be obtained for different targets (aquifers, surface ...).

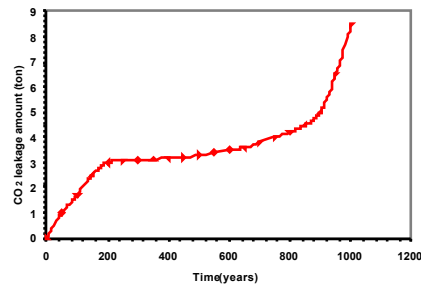


Figure 4: Cumulative  $CO_2$  leakage along the plugged well over 1000 years coming out of the reservoir

The curve present ed in Figure 4 can be divided in 3 parts. The first one (from 0 to 250 years) corresponds to  $CO_2$  penetration into the cement sheath (from the bottom of the 5'' casing). The second part of the curve (from 250 to 850 years) corresponds to the  $CO_2$  flow up in a better quality cement sheath ( 7'' casing ), which explains why the  $CO_2$  leakage amount increases less fast than between 0 and 250 years. The last part of the curve corresponds to a simultaneous  $CO_2$  leakage through the inner part of the well and via cement sheaths until the aquifer (Figure 5).

### 5.2.2. Water saturation/ $CO_2$ front propagation

Cement water saturation evolution is a relevant indicator for identi fying leakage pathways along the well. Figure 5 illustrates four snapshots which illust rate cement water saturation at four time laps (250 , 500, 850 and 1000 years).

Two main  $CO_2$  leakage pathways can be identified: one part of  $CO_2$  flows up through the cement sheaths, whereas the rest penetrates the inner part of the well by means of the 7'' casing breakthrough. This competition between the two pathways highlights the complexity of the flow up of  $CO_2$  along the well. The behavior of the well components towards  $CO_2$  and the other aggressive fluids can change drastically the leakage pathway. The difference of hydraulic charge between the  $CO_2$  propagation front and the surface leads the  $CO_2$  flow up in function of the barriers met.

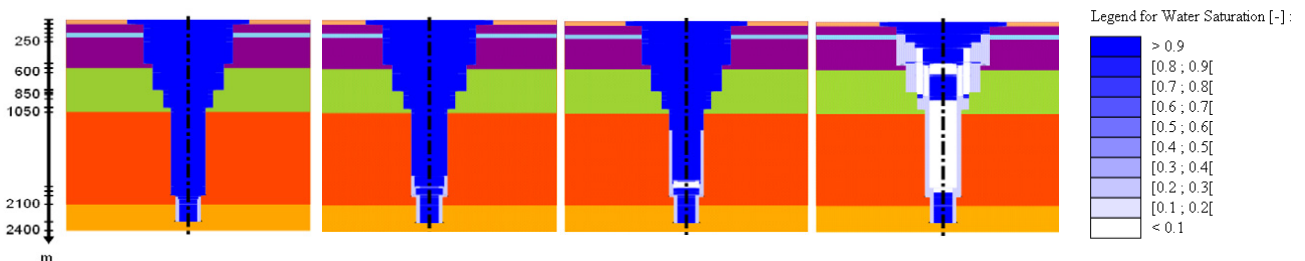


Figure 5: Water saturation evolution for the well at 250 years, at 500 years, 850 years and 1000 years (snapshots from Simeo™-Stor)

Indeed Figure 5 shows that the gas flow up is faster through the cement sheaths than through the inner part of the well. This is due to the fact that dense completion fluid present in the inner part of the well is confined; it can only flow through the part of degraded casing (7'') in contact of  $CO_2$ .

As a conclusion, the pathway the CO<sub>2</sub> will take to flow up to a target (i.e. surface and/or connected aquifers) is not obvious to assess, uncertainties of specific parameters can have a strong influence on it. In Figure 6, cement leaching degradation due to formation fluids of the Cretaceous geological layer (green) has been considered faster than in the previous simulations. In this case, CO<sub>2</sub> flows up through the inner part of the well and not along cement sheaths. Completion fluid previously confined in the inner part of the well can flow through the degraded casings in front of the Cretaceous (Green) earlier than in the previous simulations because of faster cement leaching and casing corrosion.

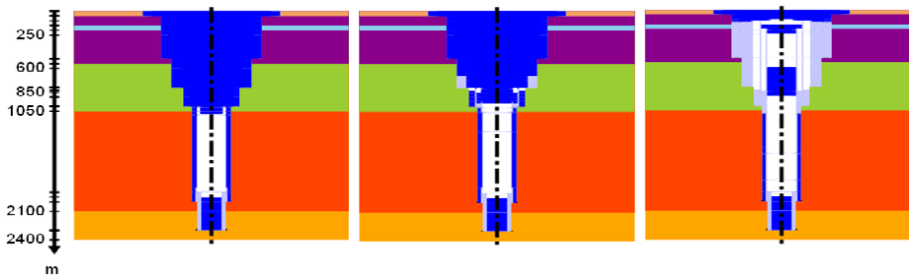


Figure 6: Water saturation of the well with different degradations conditions (t=500, t= 600, t=1000 years) (snapshots from Simeo<sup>TM</sup>-Stor)

In order to take into account all the possible leakage pathways and leakage amounts associated in a well integrity perspective, a robust methodology as the P&R<sup>TM</sup> is necessary. The complexity of the system and the interactions with its nearest environment requires assessing the uncertainties associated to well integrity conditions and to manage them.

### 5.2.3. Risk mapping

The risks dedicated to the 243 scenarios are populated in the risk matrix after 1000 years as presented in Figure 7. The probability of a scenario to occur is given on the vertical axis and its severity (in function of a CO<sub>2</sub> leakage over given period vs. stakes) on the horizontal axis.

|                    |          | Severities |     |        |       |          |         |
|--------------------|----------|------------|-----|--------|-------|----------|---------|
|                    |          | Minor      | Low | Severe | Major | Critical | Extreme |
| Probability levels | Certain  | 0          | 0   | 0      | 0     | 0        | 0       |
|                    | Almost   | 0          | 0   | 9      | 1     | 1        | 0       |
|                    | Likely   | 0          | 0   | 91     | 68    | 22       | 9       |
|                    | Possible | 0          | 0   | 8      | 16    | 0        | 8       |
|                    | Unlikely | 0          | 0   | 0      | 0     | 0        | 0       |
|                    | Rare     | 0          | 0   | 0      | 0     | 0        | 0       |

Figure 7: Population of the 243 scenarios in the risk matrix dedicated to well integrity (after 1000 years) (snapshot from Simeo<sup>TM</sup>-Stor)

Once the risk matrix populated, unacceptable well integrity scenarios can be identified from the Risk Acceptance Limit (RAL) defined with project managers and stakeholders involved in the project. Such scenarios can be the ones plotted in the warm colors of the matrix for example (orange and red zones). The identification of the risk sources for the selected scenarios from the functional analysis and the possible CO<sub>2</sub> pathways obtained from numerical simulations will lead to adapted relevant mitigations actions.

## 6. Conclusions

The P&R<sup>TM</sup> methodology constitutes a robust and reliable approach for the well integrity performance management at short, medium and long term. Risk-based approaches present an important growth in practice because of its capability to communicate easily recommendations considering owner stakes. This paper aims about

the importance of physical models on practical industrial applications. Models offer a great opportunity to risk managers to anticipate their risks and to engage operational actions to manage the performance of their structures. Quantification of mechanisms including uncertainties, ageing processes and their impact on the function of a technical system, allows assessing accurately the best strategies to design high performance structures or to manage the performance of existing structures. The proposed recommendations enable to provide justified elements as a decision making support (Which risks are unacceptable? Which actions have to be performed to mitigate them?).

The application case proposed in this paper highlights that the CO<sub>2</sub> leakage risk assessment and the potential targets identification (aquifers, surface...) have to be studied at a global scale for the well and not component by component. The functional interactions between the components are too complex to be assessed intuitively as illustrated by the possible CO<sub>2</sub> leakage pathways.

As a conclusion, the P&R<sup>TM</sup> approach and its related leakage simulation platform SIMEO<sup>TM</sup>-STOR provides an innovative decision making support tool for well integrity management in a CO<sub>2</sub> geological storage project. Already applied on numerous industrial projects, the risk-based process allowed clients to set up decisions and provide a strong support to long term safety demonstration with a high level of confidence even though uncertainty was a major issue for the projects.

## Acknowledgment

Oxand's team is acknowledged for Simeo<sup>TM</sup>-Stor development, the productive discussions and the improvements brought to this paper. We also acknowledge Schlumberger Carbon Services for the discussions about well integrity and Simeo<sup>TM</sup>-Stor capabilities.

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